

EMPIRICAL DETERMINATION OF THE TIME CONSTANT, HEAT CAPACITY AND SENSITIVITY OF EARTH'S CLIMATE SYSTEM

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Viewgraphs available on request from ses@bnl.gov

FIRST ORDER QUESTIONS

How *much* will earth's temperature change?

$$\Delta T_{\text{eq}} = \lambda^{-1} F$$

What is the forcing F ?

What is the equilibrium sensitivity λ^{-1} ?

How *fast* will earth's temperature change?

What is the $1/e$ time constant characterizing climate change τ ?

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM



Global energy balance: $C \frac{dT_s}{dt} = \frac{dH}{dt} = Q - E = \gamma J - \varepsilon \sigma T_s^4$

C is heat capacity coupled to climate system on relevant time scale

T_s is global mean surface temperature H is global heat content

Q is absorbed solar energy

E is emitted longwave flux

J is $\frac{1}{4}$ solar constant

γ is planetary co-albedo

σ is Stefan-Boltzmann constant

ε is effective emissivity

ENERGY BALANCE MODEL OF EARTH'S CLIMATE SYSTEM

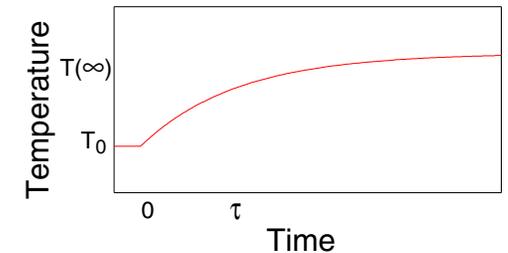


Apply step-function forcing:

$$F = \Delta(Q - E)$$

At “equilibrium”

$$\Delta T_s(\infty) = \lambda^{-1} F$$



λ^{-1} is equilibrium climate sensitivity

$$\lambda^{-1} = f \frac{T_0}{4\gamma_0 J_S} \quad \text{K} / (\text{W m}^{-2})$$

f is feedback factor

$$f = \left(1 - \frac{1}{4} \left. \frac{d \ln \gamma}{d \ln T} \right|_0 + \frac{1}{4} \left. \frac{d \ln \epsilon}{d \ln T} \right|_0 \right)^{-1}$$

Time-dependence:

$$\Delta T_s(t) = \lambda^{-1} F (1 - e^{-t/\tau})$$

τ is climate system time constant

$$\tau = C \lambda^{-1} \text{ or } \lambda^{-1} = \tau / C$$

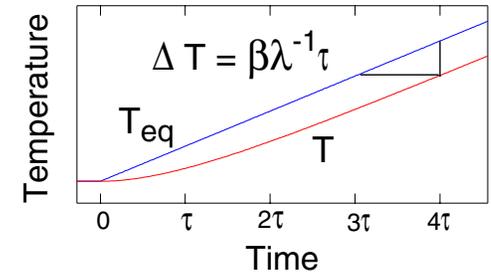
TEMPERATURE RESPONSE TO LINEARLY INCREASING FORCING



$$\beta = d\text{forcing}/d\text{time}$$

Energy balance: $C \frac{dT_s}{dt} = \beta t + \gamma J_S - \epsilon \sigma T_s^4$

Time-dependence: $\Delta T_s(t) = \beta \lambda^{-1} [(t - \tau) + \tau e^{-t/\tau}]$



λ^{-1} and τ are the same as before:

$$\lambda^{-1} = \tau / C$$

For $t/\tau \gtrsim 3$, $\Delta T_s(t) = \beta \lambda^{-1} (t - \tau)$

Temperature lags equilibrium response by: $\Delta T_{\text{lag}} = \beta \lambda^{-1} \tau$

HEAT CAPACITY OF EARTH'S CLIMATE SYSTEM FROM GLOBAL MEAN HEAT CONTENT AND SURFACE TEMPERATURE TRENDS

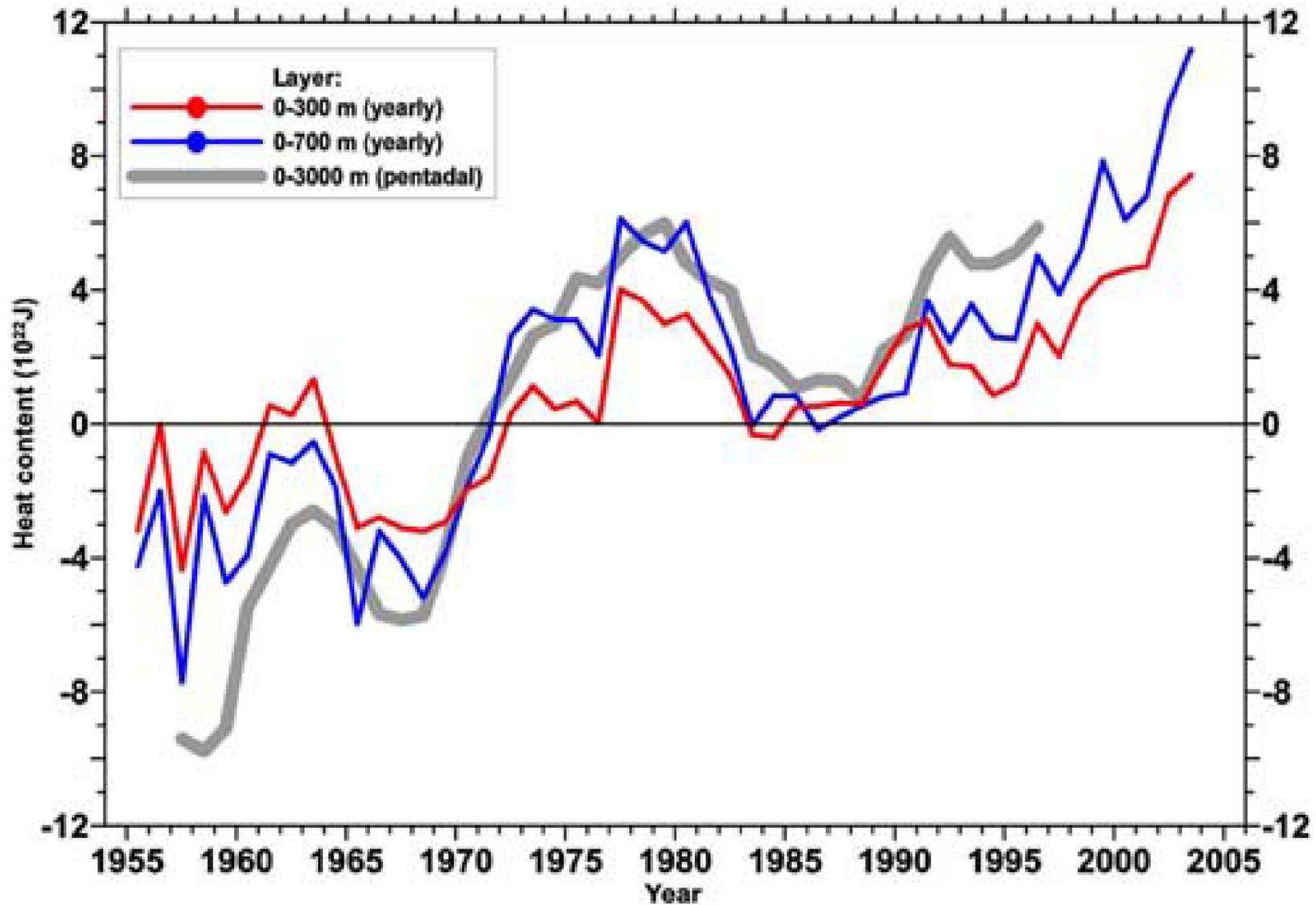
$$C = \frac{dH / dt}{dT_s / dt} = \frac{dH}{dT_s}$$

C: Global heat capacity

H: Global ocean heat content

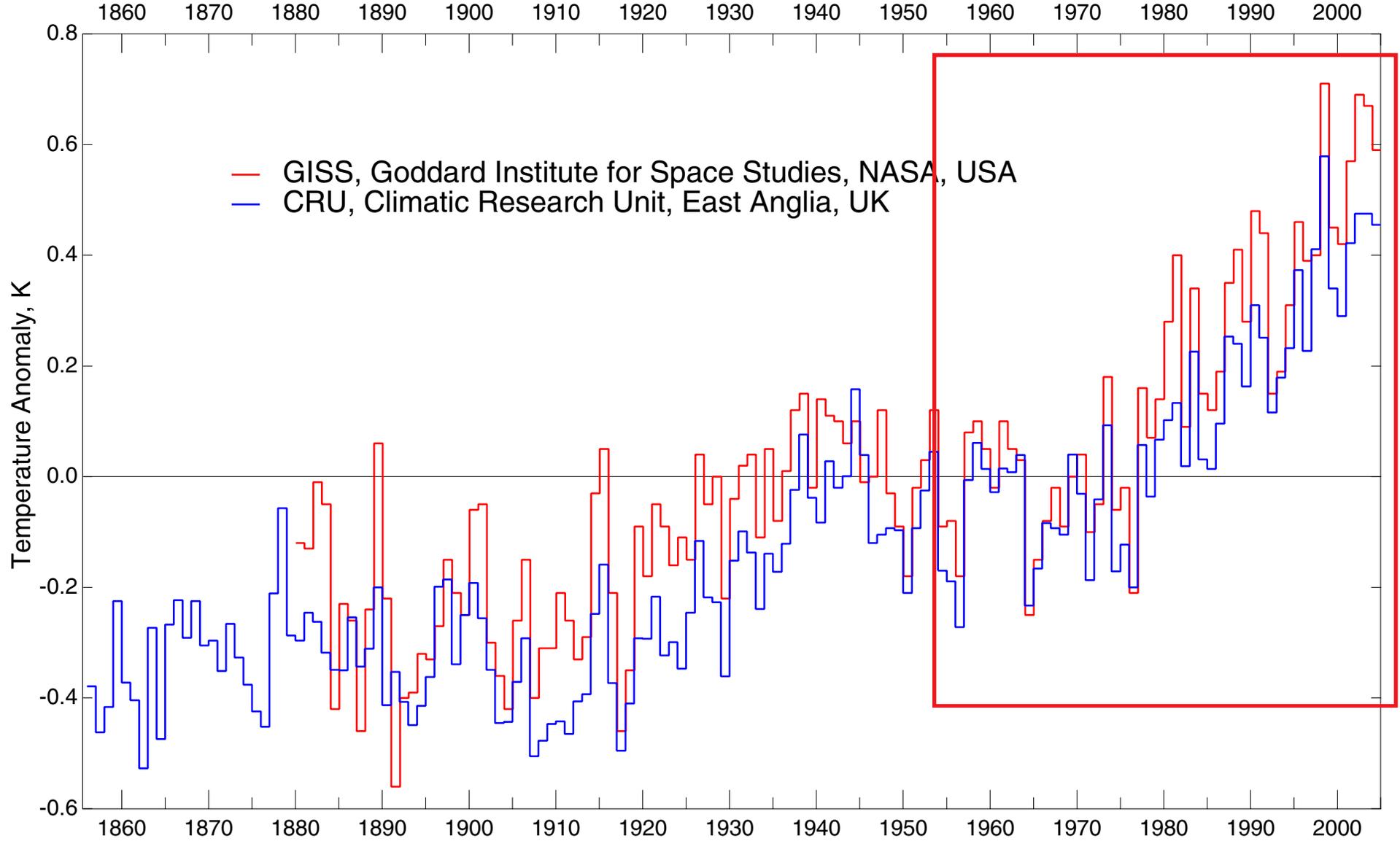
T_s: Global mean surface temperature

HEAT CONTENT OF WORLD OCEANS, 10^{22} J



Levitus et al., 2005

GLOBAL TEMPERATURE TREND OVER THE INDUSTRIAL PERIOD



DIRECT DETERMINATION OF EARTH'S HEAT CAPACITY

$$C = dH / dT_s$$

Global heat content H from Levitus et al., *GRL*, 2005.

L300: Surface to 300 m

L700: Surface to 700 m

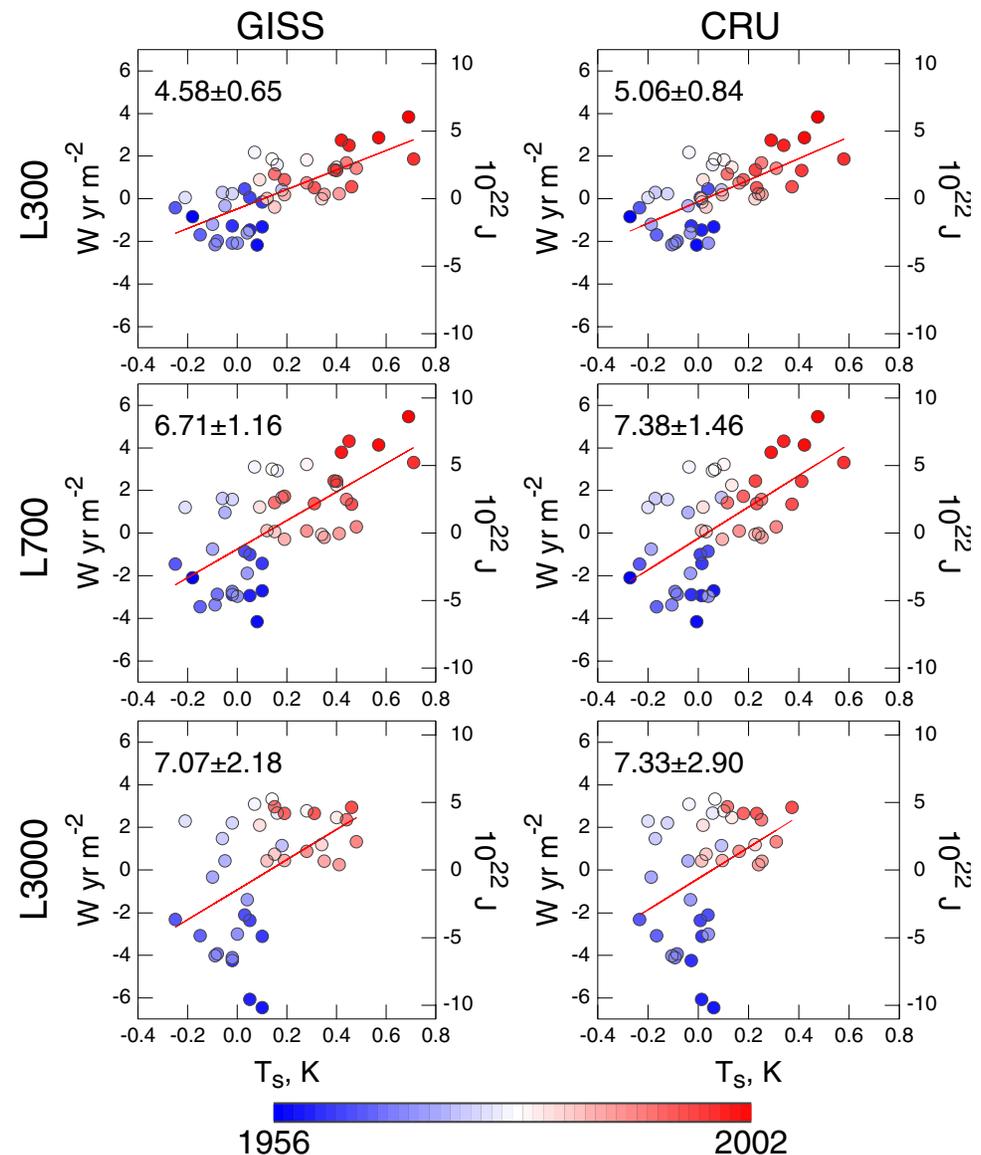
L3000: Surface to 3000 m

Global mean surface temperature T_s from Goddard Institute of Space Sciences (GISS) and Climatic Research Unit (CRU).

Slope gives heat capacity:

$$7.1 \pm 2 \text{ W yr m}^{-2} \text{ K}^{-1}$$

($\approx 76 \text{ m}$ @ 71% ocean fraction)

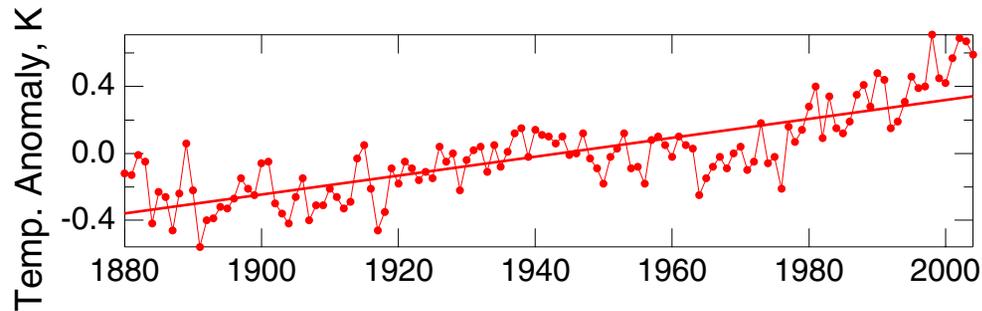


- 65-70% of heat capacity is between surface and 300 m.
- Other heat sinks raise global heat capacity to $8.5 \pm 2.4 \text{ W yr m}^{-2} \text{ K}^{-1}$.

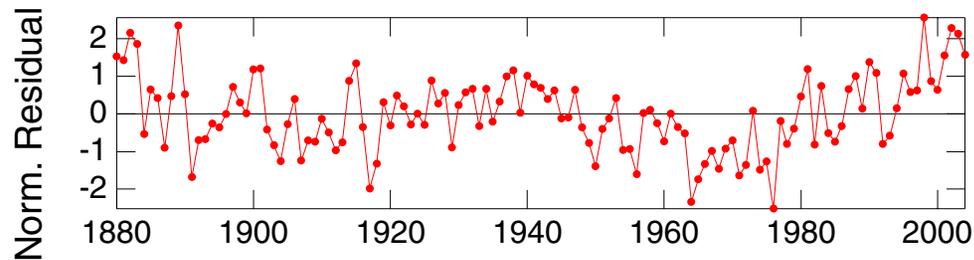
CHARACTERISTIC TIME OF EARTH'S CLIMATE SYSTEM FROM TIME SERIES ANALYSIS

DETERMINATION OF TIME CONSTANT OF EARTH'S CLIMATE SYSTEM FROM AUTOCORRELATION OF TIME SERIES

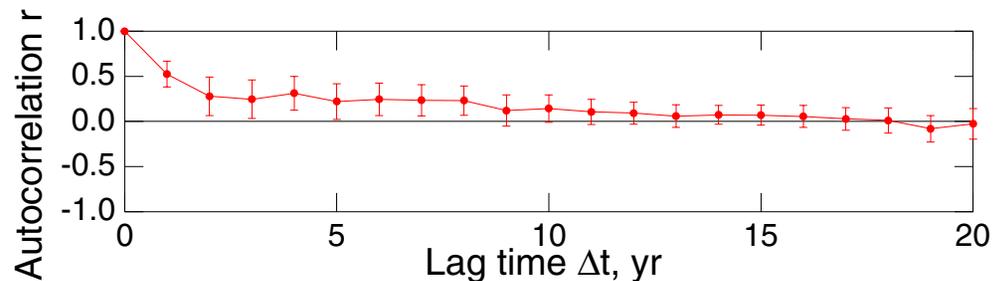
Recipe (GISS annual global mean surface temperature anomaly T_s)



1. Remove long term trend; plot the residuals:

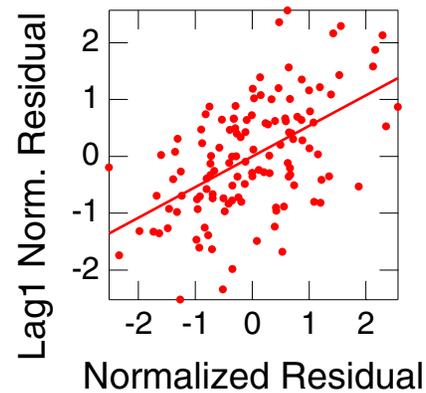


2. Calculate autocorrelogram (& standard deviations; Bartlett, 1948):

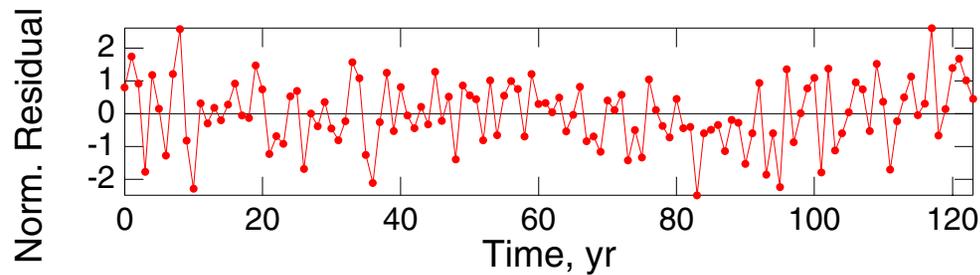


Recipe for determining climate system time constant, continued

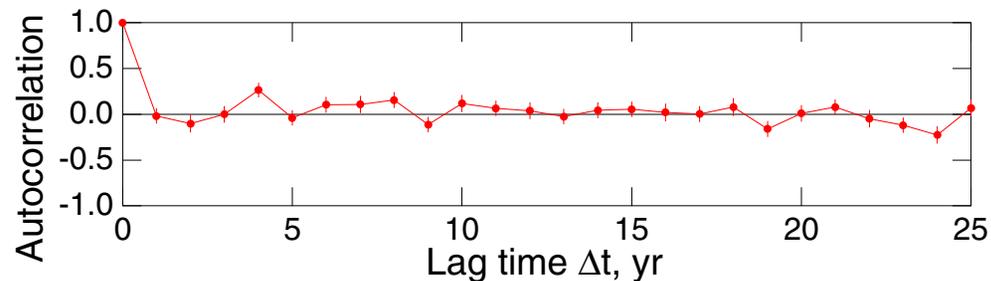
3. Examine the *lag-1* autocorrelation:



4. Remove the trend; plot the residuals:



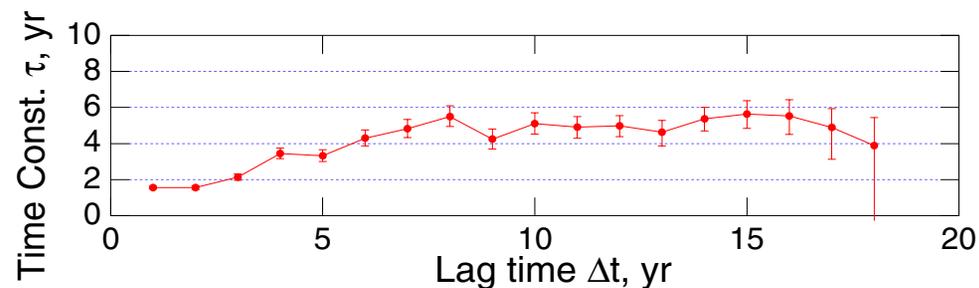
5. Examine for any remaining autocorrelation:



Recipe for determining climate system time constant, continued

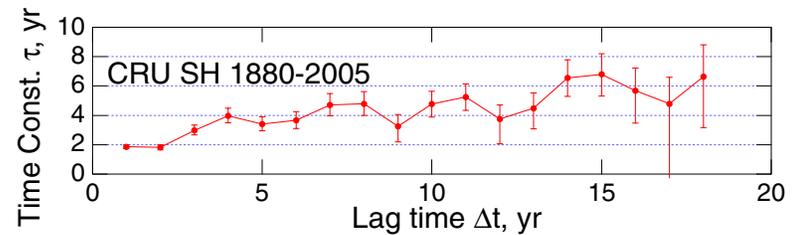
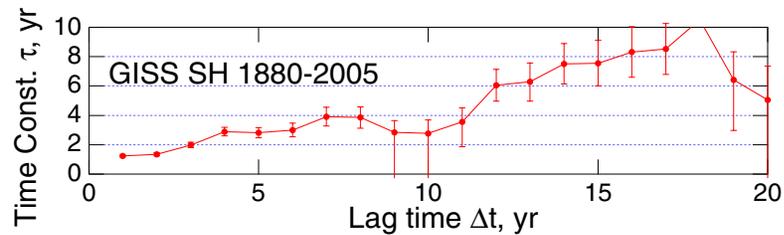
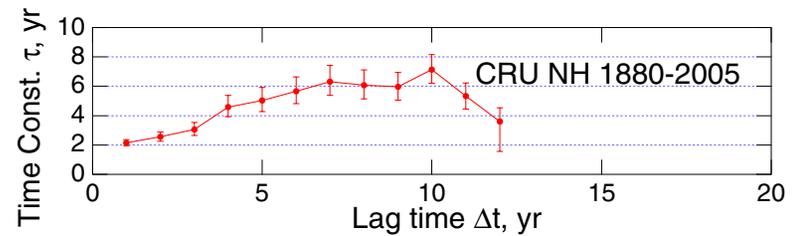
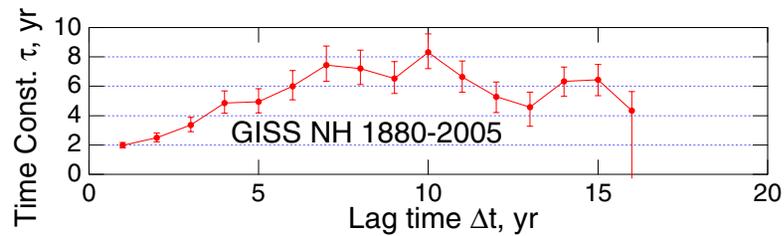
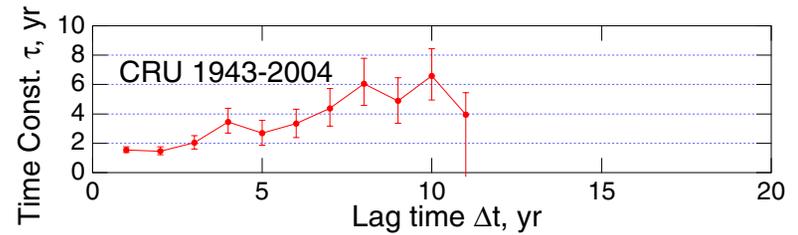
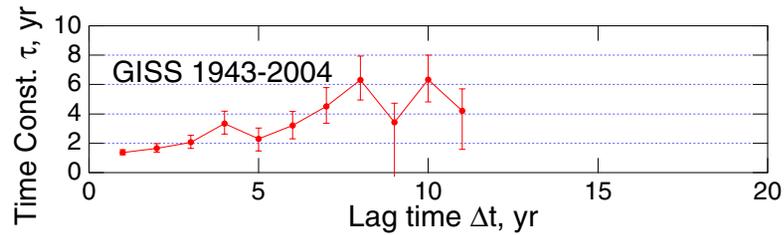
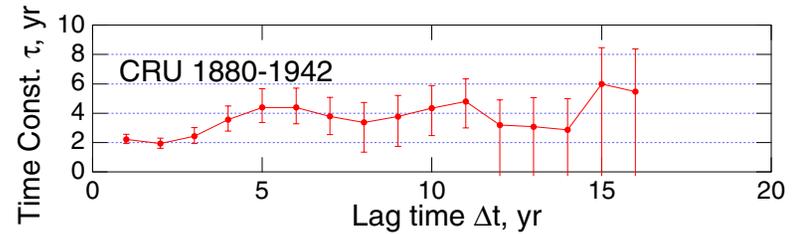
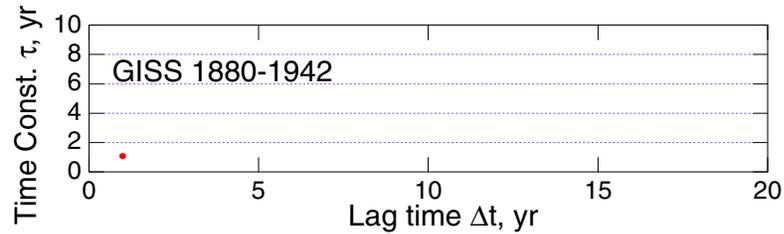
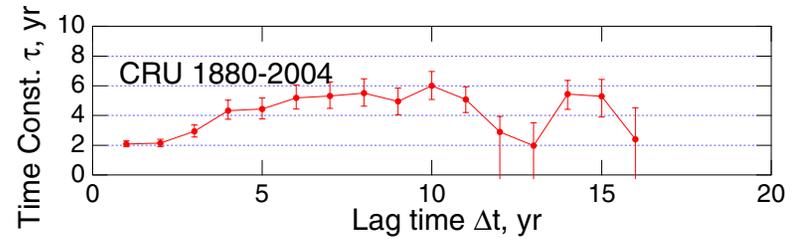
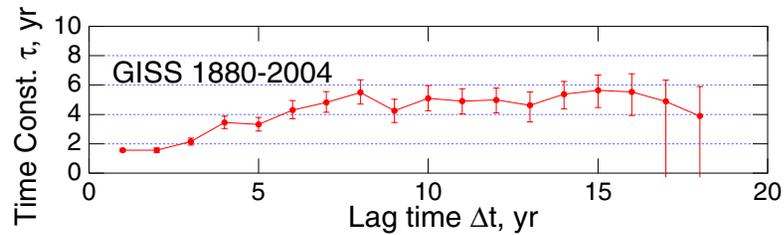
6. If no residual autocorrelation (Markov process) calculate time constant τ for relaxation of system to perturbation:

$$r(\Delta t) = e^{-\Delta t/\tau} \quad \text{or} \quad \tau(\Delta T) = -\Delta T / \ln r(\Delta T) \quad (\text{Leith, 1973})$$

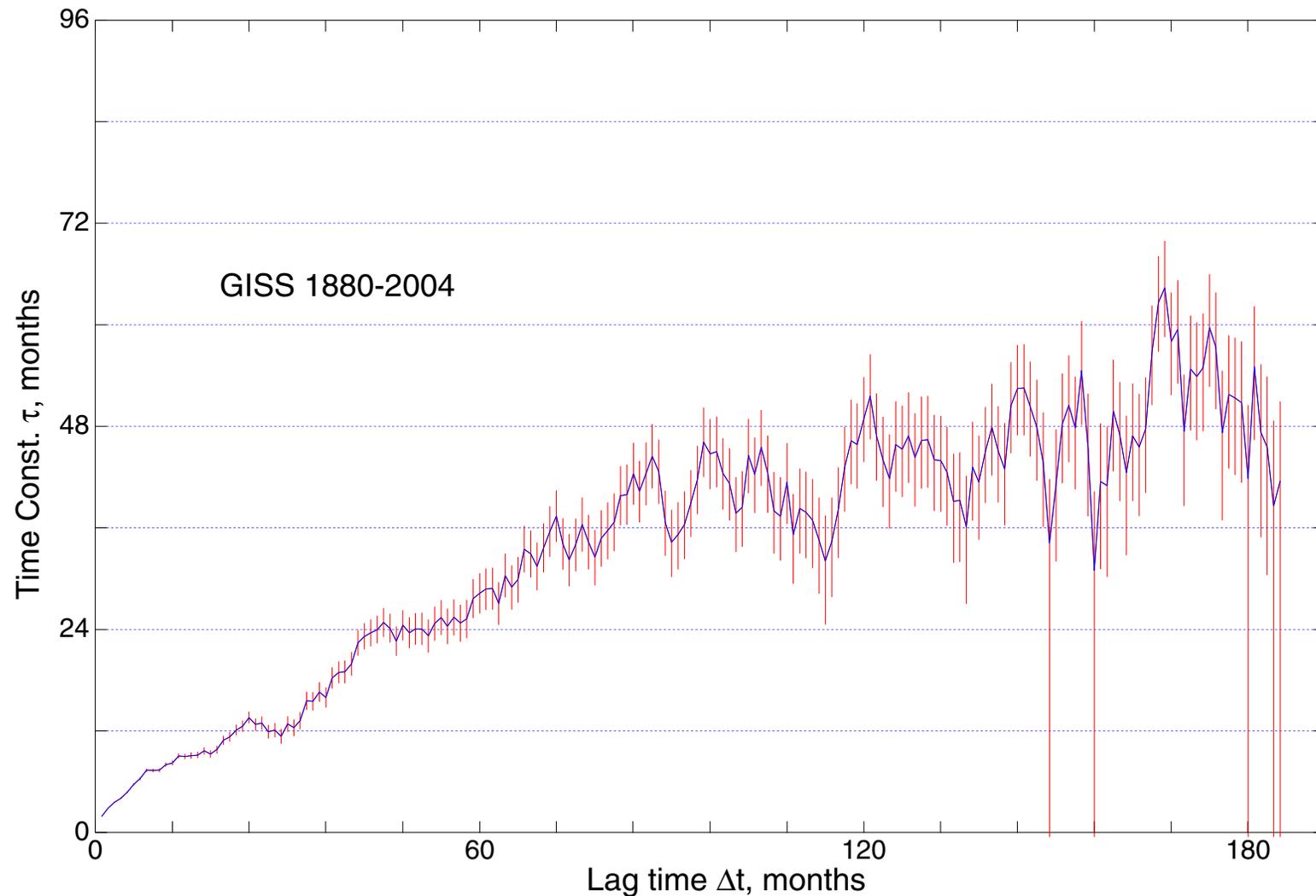


- Time constant τ *increases with increasing lag time.*
- Implies coupling of T_s to a system of longer time constant.
- On decadal scale time constant asymptotes to 5 ± 1 yr.
- This is the *e-folding time constant* for relaxation of global mean surface temperature to perturbations on the decadal scale.

THIS RESULT IS ROBUST



SAME RESULT WITH DESEASONALIZED MONTHLY DATA



- Again the time constant is about 5 yr.

CLIMATE SENSITIVITY

Equilibrium climate sensitivity $\lambda^{-1} = \tau / C$

- Time constant $\tau = 5 \pm 1 \text{ yr}$
- Heat capacity $C = 8.5 \pm 2.4 \text{ W yr m}^{-2} \text{ K}^{-1}$
- Sensitivity $\lambda^{-1} = 0.59 \pm 0.20 \text{ K} / (\text{W m}^{-2})$
- Sensitivity to forcing by $2 \times \text{CO}_2$

$$\text{For } F_{2\times} = 3.7 \text{ W m}^{-2} \quad \Delta T_{2\times} = 2.2 \pm 0.75 \text{ K}$$

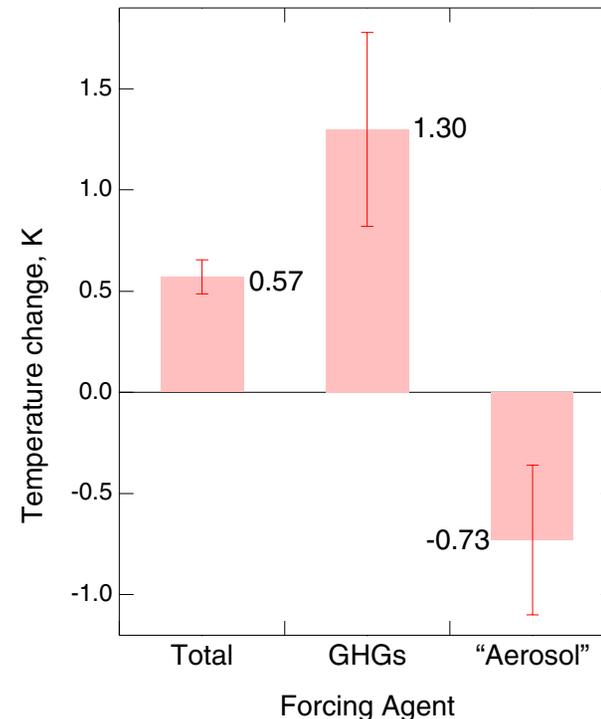
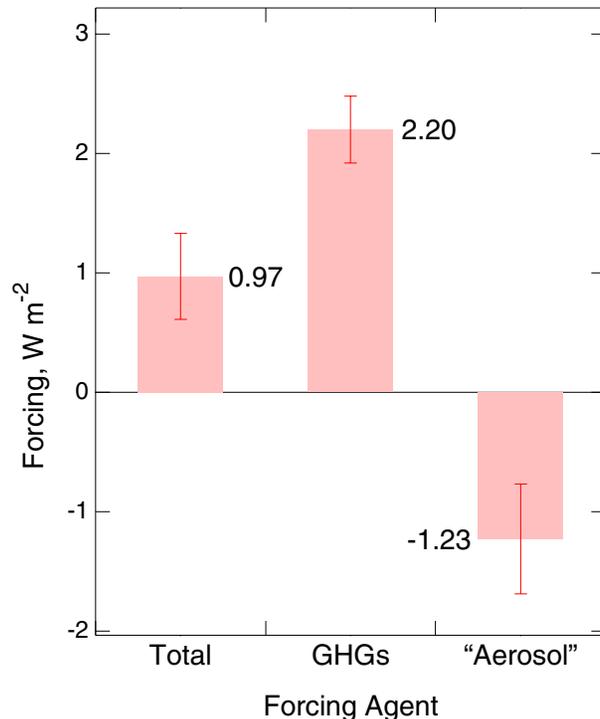
Compare IPCC AR3 (2001): $\Delta T_{2\times} = 1.5 - 4.5 \text{ K}$

INFERRED FORCING (1900 – 2000)

$$\text{Forcing } F = \Delta T / \lambda^{-1}$$

- Temperature change $\Delta T = 0.57 \pm 0.08 \text{ K}$ (Folland, 2001)
- Sensitivity $\lambda^{-1} = 0.59 \pm 0.20 \text{ K} / (\text{W m}^{-2})$
- Total forcing $F_{\text{Total}} = 0.97 \pm 0.36 \text{ W m}^{-2}$

INVERSE CALCULATION OF “AEROSOL” FORCING AND ATTRIBUTION OF TEMPERATURE CHANGE (1900 - 2000)



- “Aerosol” forcing is calculated as difference between empirically determined total forcing and greenhouse gas forcing (long lived GHGs, tropospheric and stratospheric O₃).
- Temperature change is calculated from empirically determined sensitivity, distributed according to forcings.

HOW MUCH DOES TEMPERATURE LAG THE FORCING?

Temperature response lags forcing by time τ and

$$\text{temperature } \Delta T_{\text{lag}} = \beta \lambda^{-1} \tau$$

$$\beta = d\text{forcing}/d\text{time}$$

$$\tau = 5 \text{ yr} \quad \lambda^{-1} = 0.59 \text{ K}/(\text{W m}^{-2})$$

Forcing	β	ΔT_{lag}
	$\text{W m}^{-2} \text{ yr}^{-1}$	K
Total 1900-2000	0.01	0.03
GHG only 1960-2000	0.034	0.1

Committed warming (heating in the pipeline) is minimal!

SUMMARY

- The *effective heat capacity* of Earth's climate system is $8.5 \pm 2.4 \text{ W yr m}^{-2} \text{ K}^{-1} \approx 90 \text{ m}$ of the world ocean.
- The *time constant* of Earth's climate system is 5 ± 1 years.
- Climate system response to greenhouse forcing is in *near steady state*, with little further warming (due to present GH gases) “in the pipeline.”
- The *equilibrium sensitivity* of Earth's climate system is $0.59 \pm 0.20 \text{ K} / (\text{W m}^{-2})$; $\Delta T_{2\times} = 2.2 \pm 0.75 \text{ K}$.
- This sensitivity together implies *total 20th century forcing* of $0.97 \pm 0.36 \text{ W m}^{-2}$.
- *Inferred aerosol forcing* over 20th century is $-1.23 \mp 0.46 \text{ W m}^{-2}$.

CONCLUDING OBSERVATIONS

- The *time constant, heat capacity* and *sensitivity* of Earth's climate system are *important integral properties* that should be examined in model calculations as well as observations.
- The short time constant of climate change implies that *changes in global mean surface temperature are additive*, just like forcings.
- The temperature increase due to present excess long-lived greenhouse gases over the industrial period is 1.43 ± 0.5 K, largely offset by the temperature decrease due to present excess aerosols, is *close to or already exceeds the threshold for dangerous anthropogenic warming, 1 - 2 K*.